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EDDINGTON-LIMITED X-RAY BURSTS AS DISTANCE INDICATORS. II. POSSIBLE COMPOSITIONAL EFFECTS IN BURSTS FROM 4U 1636−536

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ABSTRACT

We analyzed 123 thermonuclear (type-I) X-ray bursts observed by the *Rossi X-ray Timing Explorer* from the low-mass X-ray binary 4U 1636−536. All but two of the 40 radius-exansion bursts in this sample reached peak fluxes which were normally distributed about a mean of $6.4\times10^{-8}\ \mathrm{ergs\,cm^{-2}\,s^{-1}}$, with a standard deviation of 7.6%. The remaining two radius-expansion bursts reached peak fluxes a factor of 1.69 ± 0.13 lower than this mean value; as a consequence, the overall variation in the peak flux of the radius-expansion bursts was a factor of ≈ 2.

This variation is comparable to the range of the Eddington limit between material with solar H-fraction ($X = 0.7$) and pure He. Such a variation may arise if, for the bright radius-expansion bursts, most of the accreted H is eliminated either by steady hot CNO burning or expelled in a radiatively-driven wind. However, steady burning cannot exhaust the accreted H for solar composition material within the typical ≈ 2 hr burst recurrence time, nor can it result in sufficient elemental stratification to allow selective ejection of the H only. An additional stratification mechanism appears to be required to separate the accreted elements and thus allow preferential ejection of the hydrogen. We also observed non-radius expansion bursts that exceeded the peak flux of the faintest radius expansion bursts. For these bursts the accreted hydrogen must have been partly ejected or eliminated, but the burst flux did not subsequently reach the (higher) Eddington limit for the underlying He-rich material.

We found no evidence for a gap in the peak flux distribution between the radius-expansion and non-radius expansion bursts, previously observed in smaller samples. Assuming that the faint radius-expansion bursts reached the Eddington limit for H-rich material ($X\approx 0.7$), and the brighter bursts the limit for pure He ($X = 0$), we estimate the distance to 4U 1636−536 (for a canonical neutron star with $M_{\rm NS} = 1.4M_\odot$, $R_{\rm NS} = 10$ km) to be 6.0 ± 0.5 kpc, or for $M_{\rm NS} = 2M_\odot$ at most 7.1 kpc.

Subject headings: stars: neutron — X-rays: bursts — stars: individual (4U 1636−536) — stars: distances

1. INTRODUCTION

Thermonuclear (type I) X-ray bursts are caused by unstable burning of accreted matter on the surface of neutron stars in low-mass X-ray binary (LMXB) systems (see Lewin et al. 1993; Bildsten 1998, for reviews). Typical burst profiles exibit short rise times between $\lesssim 1$ to 10 s, and decay time scales from 10 to ~ 100 s. Model fits using a blackbody continuum to X-ray spectra during the bursts provide evidence for an initial rise in color temperature $T_{\rm bb}$, followed by a more gradual decrease back to persistent levels. This is naturally interpreted as heating resulting from thermonuclear ignition of surface fuel, followed by cooling of the ashes once the available fuel is exhausted. The inferred blackbody radius is around 10 km, consistent with expectations for a wide range of neutron-star equations of state. The time to achieve burst ignition depends primarily on the accretion rate and the H-fraction, X_0, in the accreted material; the composition at ignition, X (as well as the temperature of the fuel layer) is modified by steady hot-CNO H-burning between the bursts (e.g. Fujimoto et al. 1981). Such bursts have been observed to date from more than 70 sources (for a recent catalog see in 't Zand et al. 2004).

If the energy from the burst is released sufficiently rapidly the flux may exceed the Eddington limit, which for a sufficiently distant observer is (Lewin et al. 1993)

$$\begin{aligned} L_{\rm Edd,\infty} &= \frac{8\pi G m_{\rm p} M_{\rm NS} c[1+(\alpha_{\rm T}T_{\rm e})^{0.86}]}{\sigma_{\rm T}(1+X)}\left(1-\frac{2GM_{\rm NS}}{Rc^2}\right)^{1/2} \\ &= 3.5\times10^{38}\left(\frac{M_{\rm NS}}{1.4M_\odot}\right)\frac{1+(\alpha_{\rm T}T_{\rm e})^{0.86}}{1+X} \\ &\quad\times\left(1-\frac{2GM_{\rm NS}}{Rc^2}\right)^{1/2}\ \mathrm{ergs\,s^{-1}} \end{aligned} \tag{1}$$

where $M_{\rm NS}$ is the mass of the neutron star, $T_{\rm e}$ is the effective temperature of the atmosphere, $\alpha_{\rm T}$ is a coefficient parametrizing the T-dependence of the electron scattering opacity ($= 2.2\times10^{-9}\ \mathrm{K^{-1}}$; Lewin et al. 1993), m_p is the mass of the proton, σ_T the Thompson scattering cross-section, and X is the mass fraction of hydrogen in the atmosphere (≈ 0.7 for cosmic abundances). The final factor in parentheses represents the gravitational redshift due to the compact nature of the neutron star, which also depends upon the height of the emitting layer above the neutron star surface $R \geq R_{\rm NS}$. Once the Eddington limit is reached, the radiation forces due to the burst flux are

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sufficient to lift the outer layers of the atmosphere above the neutron star surface. Thermonuclear bursts exhibiting photospheric radius-expansion (PRE) are thus important because the peak flux can be estimated based on the gravitational redshift and atmospheric composition. If the emission is isotropic, such bursts represent a "standard candle", which can in principle allow estimates of the distance to the source (e.g. see Kuulkers et al. 2003) or the compactness of the neutron star (e.g. Damen et al. 1990).

In this series of papers, we investigate empirically the assumption that the peak flux of PRE bursts is constant for each burst source. In the first paper, we found evidence for significant variation in the peak flux of PRE bursts observed with the *Rossi X-ray Timing Explorer* (*RXTE*) from 4U 1728−34 (Galloway et al. 2003a, hereafter Paper A). The peak burst fluxes appeared to vary steadily on a timescale of a few tens of days, which was similar to the timescale at which the persistent X-ray flux was modulated. The $\approx 10\%$ rms variation in peak burst flux was attributed to varying degrees of reflection from a precessing accretion disk, with the burst emission inferred to be intrinsically isotropic. Here we present a study of the variation of the peak fluxes of PRE bursts from 4U 1636−536, through analysis of the largest sample to date, gathered from the available public data from observations by *RXTE*.

4U 1636−536 ($l = 332\overset{\circ}{.}9$, $b = -4\overset{\circ}{.}8$) is a well-studied LMXB, consisting of a neutron star in a 3.8 h orbit with an 18th magnitude star, V801 Ara (van Paradijs et al. 1990; see also Giles et al. 2002). The X-ray source exhibits a variety of rapid time variability, including kHz quasi-periodic oscillations (Wijnands et al. 1997), X-ray bursts, and burst oscillations at 579.3 Hz (Strohmayer et al. 1998a,b). Previous analyses of small numbers of X-ray bursts observed from this source by various satellites revealed that their peak fluxes appeared to be distributed bimodally in the most part, with the PRE bursts reaching a peak flux a factor of 1.7 higher than the brightest non-PRE burst (Inoue et al. 1984; Lewin et al. 1987). The measured peak fluxes of the PRE bursts were generally found to be consistent from burst to burst (e.g., Ebisuzaki 1987). The properties of the PRE bursts, along with the claimed detection of redshifted absorption features in the burst spectra (Waki et al. 1984) have led to distance estimates between 6–7 kpc (e.g. Christian & Swank 1997).

2. RXTE OBSERVATIONS OF 4U 1636−536

The High-Energy Astrophysics Science Archive Research Centre (HEASARC; \protecthttp://heasarc.gsfc.nasa.gov) contains public *RXTE* observations of 4U 1636−536 dating from shortly after the launch of the satellite on 1995 December 30. We extracted all the available public data, which at the time of writing includes observations up to 2004 March 26. We principally used data from the Proportional Counter Array (PCA; Jahoda et al. 1996) aboard *RXTE*, which consists of five identical gas-filled proportional counter units (PCUs) with a total effective area of ≈ 6000 cm^2 and sensitivity to X-ray photons in the 2–60 keV range. We have developed a pipeline processing system to identify and download newly public data from around 70 known bursting sources, including 4U 1636−536. We generated 1-s binned lightcurves from each observation, and then identified highly significant single-bin deviations from the mean count rate as burst candidates. Each such candidate was visually inspected to distinguish from other possible sources of abrupt count rate variation, including PCUs being turned on or off, or PCU breakdowns.

Once located, high time- and spectral resolution PCA data (where available) covering each burst were processed to obtain full-range spectra within intervals of 0.25–4 s (with the integration time increasing as the burst count rate decays). To take into account gradual variations in the PCA gain we generated a response matrix for each burst using PCARSP version 10.1[7], which is part of LHEASOFT release 5.3 (2003 November 17). A persistent emission spectrum extracted from a (typically) 16 s interval prior to the burst was used as the background; this approach is well-established as a standard procedure in X-ray burst analysis (e.g., Kuulkers et al. 2002, although see also van Paradijs & Lewin 1986). We estimated the persistent flux, $F_{\rm per}$, at the time of each burst by fitting the background-subtracted spectrum averaged over the entire observation (excluding the bursts) with a model consisting of an absorbed blackbody and power law.

We fitted each time-resolved burst spectrum with a blackbody model multiplied by a low-energy cutoff representing interstellar absorption with fixed abundances. The initial fitting was performed with the absorption column density $n_{\rm H}$ free to vary; subsequently, it was fixed at the mean value measured over the entire burst for the final results. The flux at the peak of the burst did not vary significantly as a function of $n_{\rm H}$. The bolometric flux at each timestep t_i was calculated according to

$$\begin{aligned} F_{{\rm bol},i} &= \sigma T_i^4 \left(\frac{R_{\rm NS}}{d}\right)_i^2 \\ &= 1.0763\times10^{-11}\ T_{{\rm bb},i}^4 K_{{\rm bb},i}\ {\rm ergs\,cm^{-2}\,s^{-1}} \end{aligned} \quad (2)$$

where $T_{\rm bb}$ is the color temperature, $K_{\rm bb} = (R_{\rm bb,km}/d_{\rm 10kpc})^2$ is the blackbody normalisation, with $R_{\rm bb,km}$ the apparent radius of the neutron star in km for a distance of $d_{\rm 10kpc} \equiv d/(10\ {\rm kpc})$. As a working definition, we considered that radius expansion occurred when 1) the blackbody normalization $K_{\rm bb}$ reached a (local) maximum close to the time of peak flux; 2) lower values of $K_{\rm bb}$ were measured following the maximum, with the decrease significant to a level of 4σ or more; and 3) there was evidence of a significant (local) decrease in the fitted temperature $T_{\rm bb}$ at the same time as the increase in $K_{\rm bb}$ (these criteria are identical to those used in Paper A). We measured the fluence $E_{\rm b}$ by integrating numerically over the measured values of $F_{{\rm bol},i}$, extrapolating the derived exponential decay curve for the cases where the burst emission lasted

[7] We note that the geometric area of the PCUs was changed for this release for improved consistency between PCUs and (e.g.) canonical models of calibration sources, particularly the Crab pulsar and nebula. These changes have the effect of reducing the measured flux compared to analyses using previous versions of the response generating tools by 12–14%. See \protecthttp://lheawww.gsfc.nasa.gov/~keith/pca_calibration_draft.ps (Jahoda et al. 2005, ApJ, submitted) for more details.

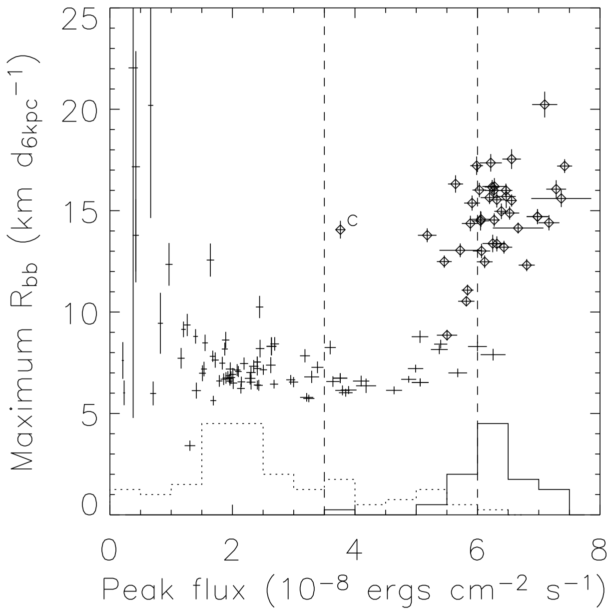

FIG. 1.— Maximum blackbody radius (for a source distance of 6.0 kpc) in the rising phase of the burst as a function of the peak flux for 78 non-radius expansion and 40 radius expansion bursts from 4U 1636−536. Error bars indicate the 1σ uncertainties on each measurement; radius-expansion bursts are additionally indicated by diamond symbols. Burst (c) is labeled (see §3.1). The dashed lines delineate the gap in the $F_{\rm peak}$ distribution inferred by Sugimoto et al. (1984). The histograms show the separate peak flux distributions of the non-radius expansion (dotted line) and radius expansion (solid line) bursts. The largest bin for the two distributions contains 18 bursts.

longer than the high-resolution spectral data (typically 200 s).

3. RESULTS

The currently available public *RXTE* data include 123 X-ray bursts from 4U 1636−536. The distribution of peak fluxes as a function of the presence or absence of radius expansion is shown in Fig. 1. The majority of the PRE bursts reached peak fluxes $F_{\rm peak}$ that were distributed normally between 5.5–7.4×10^{-8} ergs cm^{-2} s^{-1}, with a mean of 6.4×10^{-8} ergs cm^{-2} s^{-1} and a standard deviation of 7.6%. This variation was significantly greater than the typical error on the flux (~ 3%); a χ^2 calculation indicates that the hypothesis of a constant $F_{\rm peak}$ for these bursts can be excluded down to a confidence level of $< 10^{-16}$ (equivalent to $> 8\sigma$). The PRE bursts reached maximum $R_{\rm bb}$ approximately a factor of two larger than the maximum achieved during the rise for the non-PRE bursts. The weighted mean maximum radii were 14 ± 2 and 6.9 ± 1.0 km $d_{\rm 6kpc}^{-1}$, respectively. The smallest maximum $R_{\rm bb}$ reached by a burst which showed unambiguous indications of PRE was 8.8 km $d_{\rm 6kpc}^{-1}$.

We also observed 78 non-PRE bursts, with peak fluxes distributed normally between 0.21–6.3×10^{-8} ergs cm^{-2} s^{-1}. We found several bursts (both PRE and non-PRE) which reached peak fluxes between ≈ 3.5–6×10^{-8} ergs cm^{-2} s^{-1}, i.e. within the "gap" noted by Sugimoto et al. (1984) and Lewin et al. (1987). We also found two PRE bursts that reached a peak flux of around 3.7×10^{-8} ergs cm^{-2} s^{-1}, which is lower than the maximum peak flux of the non-PRE bursts. In the next section (§3.1) we describe these bursts in detail.

The 7.6% spread in peak fluxes for the brighter ($F_{\rm peak}\gtrsim 5\times10^{-8}$ ergs cm^{-2} s^{-1}) PRE bursts is similar to that measured in 4U 1728−34 (Paper A). If the variation in the peak fluxes of the bright PRE bursts from 4U 1636−536 arises from the same mechanism, we might expect to find evidence for a connection with the persistent emission, as well as for reprocessing of the burst flux (i.e. a correlation between the peak flux and fluence). While there are some indications for quasi-periodic variation at a period of ≈ 75 d in the long-term All-Sky Monitor lightcurve, this periodicity does not appear to be reflected by the peak burst fluxes. We found no significant peaks in a Lomb-Scargle periodogram of the peak fluxes as a function of time and no correlation between the peak PRE burst flux and the fluence (as was also observed in 4U 1728−34). We also found no evidence for modulation of the peak burst fluxes at the 3.8 hr orbital period (using the most recent published ephemeris; Giles et al. 2002).

3.1. *Radius-expansion at low peak flux*

We found two bursts that exhibited PRE but reached peak fluxes significantly below the maximum peak flux of the non-PRE bursts. While one of the bursts (on 1999 Sep 25 20:40:49 UT) exhibited a factor of ~ 2 increase in radius and the archetypical flat-topped flux profile of a PRE burst, the other (on 2000 Jan 22 04:43:48 UT) had much more modest expansion and an overall less compelling case for PRE. The bursts reached peak fluxes of 3.76×10^{-8} and 3.60×10^{-8} ergs cm^{-2} s^{-1}, respectively. These peak fluxes were consistent to within the errors, and were less than the mean for the remaining PRE bursts by a factor of 1.69 ± 0.13 (where the uncertainty arises primarily from the 7.6% variation in the peak fluxes of the latter sample). These bursts represent a highly significant deviation from the normally-distributed peak fluxes of the remaining PRE bursts, and lead to an overall variation of a factor of ≈ 2 in the peak fluxes of PRE bursts from 4U 1636−536.

In Fig. 2 we show the variation of spectral parameters throughout a bright PRE burst, a non-PRE burst, and one of the fainter PRE bursts. The profiles for the bright and faint PRE bursts (a, left panels and c, right panels) were similar before and after the PRE episode. However, for burst (c) the flux was approximately constant during the PRE episode at around 4×10^{-8} ergs cm^{-2} s^{-1}, i.e. at around 60% of that reached at the peak of burst (a). We note that the two faint PRE bursts were observed while the persistent 2.5–25 keV flux was unusually high, above 6×10^{-9} ergs cm^{-2} s^{-1}. We observed an insufficient number of bursts within this flux range to determine conclusively whether the peak flux distribution differed from that at lower persistent fluxes.

Both $R_{\rm bb}$ and $T_{\rm bb}$ measured at the time of maximum flux of the two faint PRE bursts were, individually, within the ranges spanned by the brighter PRE bursts. Thus, the lower peak fluxes were not solely due to unusually low values of either of these parameters. We note that, as with previous observations (Sugimoto et al. 1984), the radius maximum during the majority of the PRE bursts was generally achieved prior to the maximum measured flux. Thus, the luminosity continued to increase throughout the PRE episodes, as has been found on other sources (e.g. Galloway et al. 2003b). The

two faint PRE bursts were notable exceptions; for those bursts, the peak flux coincided with the peak radius. Given the relatively wide field of view ($\approx 1°$) of *RXTE* it is conceivable that these fainter PRE bursts actually originated from a previously unknown and more distant field source. The detection of burst oscillations at 580 Hz in the burst on 1999 September 25 (Fig. 2c; Giles et al. 2002; Muno et al. 2001) effectively rules out this possibility, at least for that burst.

A third burst, observed on 2002 January 15 14:08:16 UT, showed evidence of a local radius maximum, but at an even lower peak flux than burst (c). During this burst the flux rose and decayed gradually, possibly with more than one local maxima. The maximum radius reached was only somewhat below that of burst (c) and, like that burst, was accompanied by a local minimum in $T_{\rm bb}$. However, the peak flux was below 2×10^{-8} ergs cm^{-2} s^{-1}, i.e. less than 25% the peak flux of burst (a); furthermore, the possible radius expansion episode occurred well before the peak flux was reached, at a flux of only around 1.3×10^{-8} ergs cm^{-2} s^{-1}. This burst was substantially different in character from the other two faint PRE bursts. It reached a comparable peak flux and was observed at a similar persistent flux level as were four double-peaked bursts, also observed by *RXTE*. These bursts (on 2001 September 5 08:15:04 UT, 2001 October 3 00:22:18 UT, 2002 January 8 12:22:44 UT and 2002 February 28 23:42:53 UT) exhibited double peaks in the bolometric flux, as has been observed previously from this source (Sztajno et al. 1985). In contrast to the double-peaked bursts observed previously, in which the first peak was consistently higher, 3 of the 4 double peaked bursts observed by *RXTE* reached a higher flux during the second peak. The relative fluxes of the two peaks varied from $\approx$ 1–3. Two of the four double-peaked bursts exhibited a local maxima in the radius (and a corresponding minimum in temperature) coincident or just after the first flux peak, similar to what is generally interpreted as evidence for PRE. Because of this similarity, we conclude that the 2002 January 15 14:08:16 UT burst was not a genuine PRE burst, but instead arose from the same phenomenon which gives rise to the double-peaked bursts.

4. DISCUSSION

We have studied the peak fluxes of radius expansion bursts from 4U 1636−536 and found the largest range yet seen in any LMXB. While the fractional variation of peak fluxes exceeded the expected range of the Eddington limit between atmospheres with H at cosmic abundances ($L_{\rm Edd,H}$, with $X\simeq0.7$) and with pure He ($L_{\rm Edd,He}$, $X=0$; e.g. Kuulkers et al. 2003), the distribution of peak fluxes was nearly bimodal, with the mean peak flux for the majority of the PRE bursts being a factor of 1.69 ± 0.13 higher than the peak fluxes for the faint PRE bursts.

In a previous investigation of X-ray bursts from 4U 1636−536 with *Tenma*, Sugimoto et al. (1984) observed a gap in the distribution of peak fluxes of bursts and identified the lower and upper boundaries of this gap as the Eddington limits for H-rich $L_{\rm Edd,H}$ and pure He fuel $L_{\rm Edd,He}$, respectively. According to their interpetation, the increase in radius which was observed during the PRE bursts from 4U 1636−536 was accompanied by

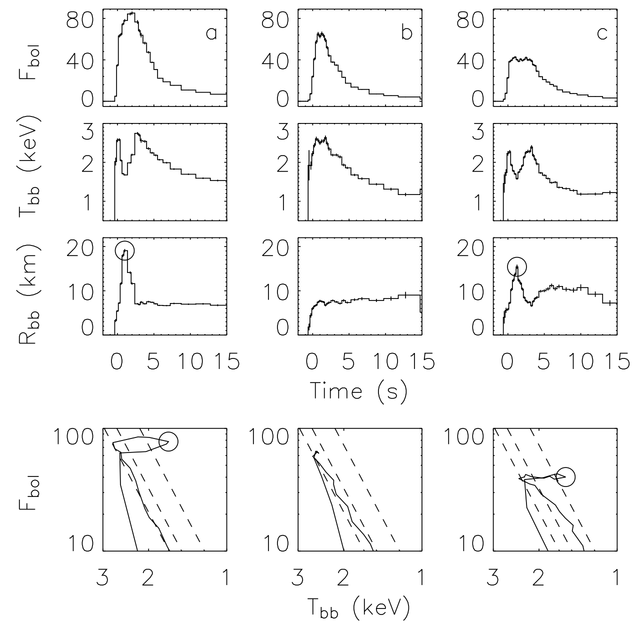

FIG. 2.— Thermonuclear bursts from 4U 1636−536 showing radius expansion over a wide range of peak fluxes. From left to right, we show a PRE burst with strong radius expansion, observed on 1998 Aug 20 03:40:09 UT; a non-PRE burst observed on 2000 Jan 22 01:46:23 UT; and a faint PRE burst observed on 1999 September 25 20:40:49 UT. From top to bottom, the panels show for each burst the time evolution of the bolometric flux $F_{\rm bol}$ (in units of 10^{-9} ergs cm^{-2} s^{-1}), the fitted blackbody temperature $T_{\rm bb}$, the blackbody radius $R_{\rm bb}$ (assuming a source distance of 6.0 kpc), and finally the path traced by the burst in $T_{\rm bb}$–$F_{\rm bol}$ space. The circles in the lower two panels in each column indicate the time of maximal radius expansion, where present. The 3 dashed lines in each of the bottom panels represent the expected curves for blackbody emission from a neutron star with apparent radius 8, 10, and 15 km (moving left to right, respectively). Error bars represent the 1σ uncertainties.

ejection of an outer, H-rich layer, exposing the underlying pure-He layer below. Bursts that never reached $L_{\rm Edd,H}$ did not exhibit PRE, while the characteristic flux limit for bursts that did exceed $L_{\rm Edd,H}$ switched to $L_{\rm Edd,He}$, which is a factor of 1.7 higher.

In this paper, we reported the observation of two PRE bursts that were apparently limited by $L_{\rm Edd,H}$ instead of $L_{\rm Edd,He}$. This appears to confirm the hypothesis of Sugimoto et al. (1984). For those bursts, the effective Eddington limit could have remained at $L_{\rm Edd,H}$ if the burst energy was insufficient to drive off the outer H-rich layer. However, we also found a significant overlap between the peak flux distributions for the PRE and non-PRE bursts, without the gap found in earlier samples. Bursts with peak fluxes within the range $\approx$ 3.5–6×10^{-8} ergs cm^{-2} s^{-1} were, however, relatively infrequent. This strongly suggests that the previously observed gap was merely a consequence of small burst samples, specifically 12 for the study of Sugimoto et al. (1984), and 27 for that of Lewin et al. (1987), with only 3 radius expansion bursts in each sample.

Four bursts observed by *RXTE* that peaked between the putative $L_{\rm Edd,H}$ and $L_{\rm Edd,He}$ values exhibited no evidence of PRE (an example is shown in Fig. 2b). In order for these bursts to have exceeded $L_{\rm Edd,H}$, the majority of the accreted H must have been ejected, but subsequently the flux must have remained below the effective Eddington limit for the residual material. The fact that no ob-

servational evidence of this ejection is seen suggests that the ejected material becomes transparent on a timescale less than the 0.25 s bin time of our time-resolved spectra.

Ejection of the accreted hydrogen likely requires that the accreted material first becomes highly stratified. In a well-mixed atmosphere, the H and He nuclei are efficiently coupled to the electrons (on which the radiation forces act) through Coulomb colisions, thus preventing any separation of the elements during the radius expansion episode. Variation in the H-fraction with depth may arise via a number of mechanisms, such as steady H burning between the bursts or via convective mixing of deeper material during the previous X-ray bursts. However, as we show below, the properties of the X-ray bursts from 4U 1636−536 place strong constraints on these mechanisms.

In order to make a rough estimate for the requirements of the ejection of the H layer during a burst, we assume that all the radiation (emitted at $\simeq L_{\rm Edd,H}$) during the radius-expansion episode is imparted as kinetic energy to the H layer. Since the H layer needs to be ejected in a short time $t_e \lesssim 1$ s, the total energy available is simply $t_e L_{\rm Edd,H} \simeq 2\times10^{38}$ergs. This amount of energy can unbind a layer of pure hydrogen of total mass

$$\begin{aligned} m_{\rm H} &\simeq \frac{L_{\rm Edd,H} t_e R_{\rm NS}}{G M_{\rm NS}} \\ &= 10^{18}\left(\frac{L_{\rm Edd,h} t_e}{2\times10^{38}\ {\rm ergs}}\right)\left(\frac{R_{\rm NS}}{10^6\ {\rm cm}}\right) \\ &\quad\times\left(\frac{M_{\rm NS}}{1.4\ M_\odot}\right)^{-1}\ {\rm g}, \end{aligned} \tag{3}$$

which extends down to a column depth of

$$\begin{aligned} y_{\rm H} &\simeq 10^{6}\left(\frac{L_{\rm Edd,h} t_e}{2\times10^{38}\ {\rm ergs}}\right)\left(\frac{R_{\rm NS}}{10^6\ {\rm cm}}\right)^{-1} \\ &\quad\times\left(\frac{M_{\rm NS}}{1.4\ M_\odot}\right)^{-1}\ {\rm g\ cm^{-2}}\ . \end{aligned} \tag{4}$$

For the burst to be subsequently limited by the pure-He Eddington limit, the material below this column depth must be practically hydrogen free. This degree of stratification is rather difficult to achieve on an accreting neutron star, as we discuss below.

Cumming & Bildsten (2000) estimate the column depth at which hydrogen runs out to be

$$y_{\rm d} \simeq 7\times10^{8}\left(\frac{\dot m}{0.01\dot m_{\rm Edd}}\right)\left(\frac{0.01}{Z_{\rm CNO}}\right)\left(\frac{X_0}{0.71}\right)\ {\rm g\ cm^{-2}}\ , \tag{5}$$

where $\dot m$ is the mass accretion rate, $Z_{\rm CNO}$ is the mass fraction of CNO nuclei, and X_0 is the mass fraction of hydrogen in the accreting material. For this column depth to be comparable to the requirement derived in equation (4), the accretion rate or the mass fraction of CNO nuclei in 4U 1636−536 have to be very different than what is normally assumed. Depletion of hydrogen below a column depth of $\simeq 10^6$ gr cm^{-2} is possible, according to Fushiki & Lamb (1987), if compressional heating is taken into account, the local accretion rate is comparable to the Eddington limit, and the core temperature of the neutron star is $\sim 10^7$ K. This is again a rather implausible combination, since a high rate of accretion in a persistent source, such as 4U 1636−536, is inconsistent with a cool neutron-star core (see, e.g., Brown et al. 1998).

Convective mixing of deeper material during the previous X-ray burst also appears to be incapable of reducing the abundance of hydrogen at columns larger than $\simeq 10^6$ gr cm^{-2}. Indeed, the convective zone in the simulations by Woosley et al. (2004) reached up to column depths that were at least two orders of magnitude larger than required. The properties of the bursts in 4U 1636−536 thus strongly suggest that there is an additional source of stratification which acts to separate the accreted elements, and allow the majority of the accreted H to be ejected during the brightest bursts.

In Paper A, we also explored in detail the possibility that variations in $F_{\rm peak}$ could arise through systematic instrumental or analysis-related biases. For example, we considered the effect of deviations of the true emission spectrum from perfect blackbodies. Implicit in our estimation of the bolometric fluxes in equation (2) is a correction to the flux measured in the PCA bandpass; this correction adds around 7% to the peak 2.5–20 keV PCA flux of radius expansion bursts. Should the emitted spectrum deviate significantly from a blackbody, equation (2) will not give the correct bolometric flux, potentially giving rise to spurious bolometric flux variations. As with 4U 1728−34, variations in the flux contribution from outside the PCA band of many times the typical bolometric correction would be required to account for the 30% variation in the peak flux of the majority of the radius expansion bursts from 4U 1636−536. We consider this unlikely. It is even less likely that such effects could account for the factor of ≈ 2 variation we observe in the peak fluxes of all the PRE bursts from 4U 1636−536. Similarly, while variations in the persistent (non-burst) emission could in principle give rise to spurious scatter in the peak burst fluxes, the variation would have to be several times the total persistent flux level in the 2.5–25 keV band to account for the peak flux variation we observe.

Although we found no evidence for quasi-periodic variation in the peak fluxes of bursts from 4U 1636−536, or correlations between the peak PRE burst flux and fluence, we cannot completely rule out reprocessing as a contributing factor to the 7.6% peak flux variation of the bright PRE bursts. The lack of detectable quasiperiodic variations in the peak burst fluxes could result from inadequate sampling provided by the burst times, or possibly the intrinsic variability is aperiodic. As for the lack of a correlation between $E_{\rm b}$ and $F_{\rm peak}$, the burst profiles from 4U 1636−536 were much more variable than those of 4U 1728−34, so that other (possibly related) variations between these properties could perhaps mask an underlying correlation resulting from reprocessing.

An alternative explanation for the low peak flux PRE bursts is that they arise from ignition of material confined to some fraction of the neutron star. Some authors have suggested that such confinement may occur as a result of the influence of the neutron star's magnetic field on the fuel layer, or as a consequence of rapid rotation (e.g. Sztajno et al. 1985). While recent modelling indicates that rotation may instead enhance spreading (Spitkovsky et al. 2002), variations in the properties of

bursts with $\dot{M}$ from some sources suggest uneven distribution of fuel over the neutron star (e.g. Bildsten 2000). This possibility may also help to explain the observation of double- (Sztajno et al. 1985) and even triple-peaked (van Paradijs et al. 1986) bursts from 4U 1636−536. We also observed four double-peaked bursts in the *RXTE* sample. Confinement of the burst fuel could result in weaker radius-expansion bursts if the local Eddington limit was reached, but only over a fraction of the neutron star surface. In that case, expansion of the photosphere would still occur, at much lower total luminosity. If the expansion of the burning region of the photosphere went to sufficiently large radii that it appeared isotropic to a distant observer, the result might be a burst which appeared similar to a normal radius expansion burst, but at a significantly lower peak flux. This explanation appears inconsistent with the observed radii in the tail of the faint PRE bursts, which are in excess of that of some of the brighter PRE bursts. It would also require that the factor of 1.7 between the peak fluxes of the two groups of PRE bursts was a coincidence. We note that several other explanations have been proposed to explain the bursts with multiple peaks (Fujimoto et al. 1988; Melia & Zylstra 1992).

Previous estimates of the distance to 4U 1636−536 at between 6–7 kpc relied on the identification of the peak flux of the PRE bursts as $L_{\rm Edd,He}$ (Ebisuzaki 1987), in addition to a gravitational redshift measured from absorption features in the burst spectra (Waki et al. 1984). While absorption features have now been detected in burst spectra from other sources using more modern, high-resolution spectroscopic instruments (Cottam et al. 2002), it is widely thought that the earlier detections using proportional counters were more likely to arise from instrumental effects. Without the absorption line measurement, the analysis of Ebisuzaki (1987) likely cannot substantially constrain the distance to 4U 1636−536. Despite the increase in measurement precision for peak burst fluxes with *RXTE*, the dominant uncertainty for distance estimates to most bursting sources remains the atmospheric composition, i.e. the value of X in equation 1. With the detection of PRE bursts that apparently reach either $L_{\rm Edd,H}$ or $L_{\rm Edd,He}$, the compositional question in 4U 1636−536 is resolved, and we can make distance estimates using either group of bursts. On correcting the observed fluxes for the gravitational redshift at the surface of a $1.4M_\odot$ NS with $R = 10$ km, the fainter PRE bursts (which we assume reach $L_{\rm Edd,H}$) lead to a distance estimate of 5.95 ± 0.12 kpc. The distance estimate assuming that the brighter PRE bursts reach $L_{\rm Edd,He}$ instead is fully consistent with this value at 6.0 ± 0.5 kpc, where the uncertainty arises from the standard deviation of the peak fluxes for this larger group. From the faintest of this group of bursts we can derive a maximum distance of 6.6 kpc, or more conservatively (for a $2M_\odot$ NS) 7.1 kpc.

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